AUV Turbulence Measurements in the LOCO Field Experiments

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LONG-TERM GOAL

The long-term goal of this project is to quantify the role of turbulence and fine scale vertical shear and buoyancy on the formation, evolution, and breakdown of plankton thin layers. Particular attention is given to understanding the relationship of the space and time statistics of the physical fields to that of the plankton thin layers.
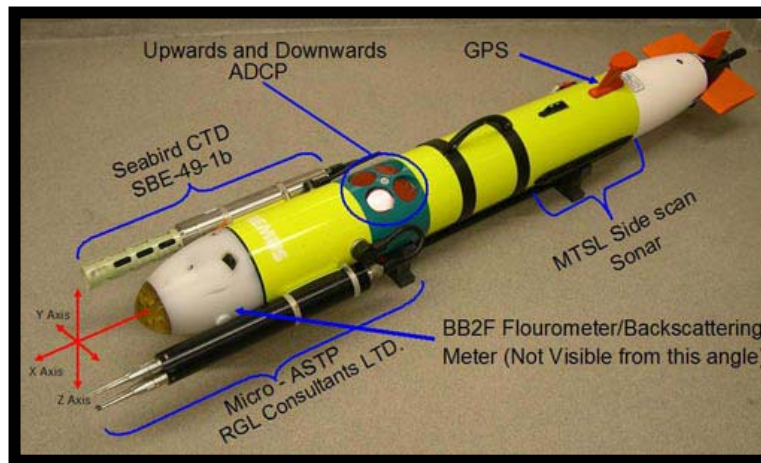
SPECIFIC PROJECT OBJECTIVES

(1) Quantify the space and time statistics of the turbulent field both within and around thin layers. Estimate the micro and fine scale parameters: the turbulent dissipation rate, the turbulent rms velocity, the turbulent eddy diffusivity, fine scale velocity shear, and fine scale stratification.

(2) Quantify the temporal and spatial scales of thin layers of phytoplankton.

(3) Quantify the role of physical processes, such as turbulence mixing (diffusion), shear dispersion, and mean current advection on the temporal and spatial distribution and evolution of thin layers in the coastal ocean.

APPROACH

The observational approach is to use the Autonomous Underwater Vehicle, T (Turbulence) -REMUS See Figure 1. T-REMUS is a custom designed REMUS 100 vehicle manufactured by Hydroid Inc, containing the Rockland Scientific Inc. MicroASTP (Lueck, 2002), an upward and downward looking 1.2 mHz ADCP, a FASTCAT CTD, and a Wet Labs BB2F Combination Spectral Backscattering Meter/ Chlorophyll Fluorometer**. In addition the vehicle contains a variety of "hotel" sensors which measure pitch, roll, yaw, and other internal dynamical characteristics. This suite of sensors allows quantification of the key dynamical and kinematical turbulent and fine scale physical and biological processes (Levin and Lueck, 1999; Goodman, 2006). The turbulence measurements are made concomitantly with very high spatial resolution measurements of chlorophyll fluorescence and optical scattering at 470 nm and 700 nm wavelength.

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Figure 1. The SMAST T-REMUS Autonomous Underwater Vehicle. It is 2.0 m long, 20 cm diameter, and 63kg mass. Shown are the various micro and fine structure sensor systems. These include the Rockland Scientific Inc. MicroASTP for turbulence measurements, the Seabird FASTCAT CTD, an upward and downward looking 1.2 mHz ADCP, a Side-Scan Sonar, and the WETLABS Combination Fluorometer and Backscattering Meter (BB2F). The vehicle is also equipped with a variety of "hotel" sensors which measure pitch, roll, yaw, and many other internal characteristics.

EFFECT TO THE ENVIRONMENT

(1) Because the AUV is battery powered there is no waste product and no harm to the environment occurs.

(2) All operations were conducted in accordance with the LOCO permit. Figure2b shows the track of the AUV during LOCO experiments.

(3) After the experiments, all equipment was recovered.

WORK COMPLETED/ PRELIMINARY RESULTS

Two highly successful experiments were completed in LOCO 2005 and LOCO 2006 at the Monterey Bay site, centered near 36.93 N, 121.92W. See figure 2. T-REMUS tracks are shown in Figure 2b. During both LOCO 05 and LOCO 06 the T-REMUS performed flawlessly and had a remarkable 100 % data return. Data processing is completed for both LOCO 05 and 06 experiments with analysis now seriously underway. We are preparing our first LOCO manuscript "Turbulence Observations from a Small AUV" for submission to a special JMS issue on turbulence as apart of the May 2007 University of Liege Conference "Turbulence Revisited".

In LOCO 05, the T-REMUS performed a series of rectangular runs of sides ~2.5 km, centered around the principal LOCO moorings (fig 2b). The vehicle was operated with in a yoyo mode with a descent/ascent angle of 1 degree. This allowed thin layers to be resolved to 2 cm thickness. During the four week experiment, eight such runs were performed, four of which were nighttime runs between

11:00 PM PDT and 1: 00 AM PDT, the time period of expected maximum occurrence and intensity of thin plankton.
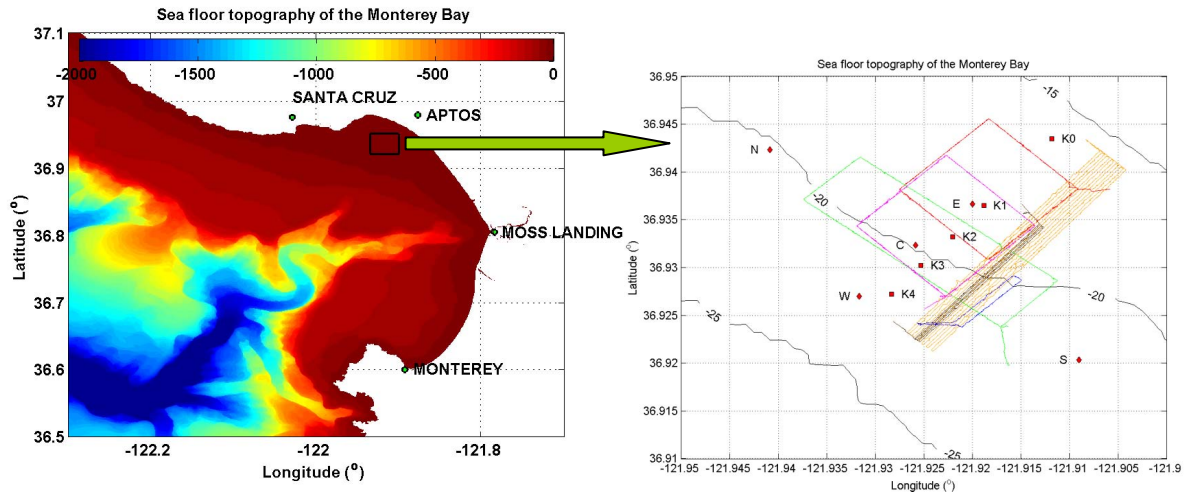
Figure 2. a) Map of the complex topography within and offshore of Monterey Bay.
b) Detailed map showing the tracks of the T-REMUS AUV during LOCO.
*Also showed are the location of the fixed LOCO 2005 and 2006 stations.*

In LOCO 06 the sampling strategy for the T -REMUS was changed to increase horizontal resolution and to more closely parallel the fixed LOCO moorings. The T-REMUS tracks are indicated by the salmon-colored lines in fig 2b. The vehicle again was deployed in a yoyo mode but with a descent/ascent angle of 5 degrees. This allowed a finer vertical resolution and some aspects of the spatial structure of internal solitary waves to be obtained.

In both LOCO 05 and 06, the AUV obtained turbulent dissipation rate, fine scale shear, buoyancy frequency, chlorophyll a, and optical backscattering at blue and red wavelengths. In both year experiments, the chlorophyll a and backscattering data showed significant thin layers. LOCO 2005 occurred entirely outside of the upwelling season of Monterey Bay. LOCO 2006 took place at the end upwelling season.

(1) The statistics of turbulence within the thin layers and out of thin layers.

Fig 3 shows a histogram of the dissipation rate within and outside of the thin layers observed. Left two panels were collected during LOCO 2005, while the right two panels are collected in LOCO 2006. Comparison of the left two panels (LOCO 2005) shows that the average dissipation rate in the thin layer (upper panel) was larger than that out of thin layer (lower panel). However there is no such trend in LOCO 2006 data. The LOCO 2005 results appear different from that of Dekshenieks et al. (2001) observations in East Sound Washington in the summer of 1996 who found that when the Richardson number dropped below 0.25, and presumably strong turbulent occurred, thin layers were not present. It should be noted that there was no direct measurement of the turbulent kinetic energy in the East Sound experiments. More significantly, the differences in the results from the two data sets might be due to different type of phytoplankton dominating each of the respective experimental sites at the time of the experiments. The LOCO 2005 site was dominated by a motile dinoflagellate *Akashiwo Sanguinea*

while the East Sound site was dominated by a diatom *Pseudo-nitzschia*. LOCO 2006 also had an abundant amount of *Pseudo-nitzschia*.
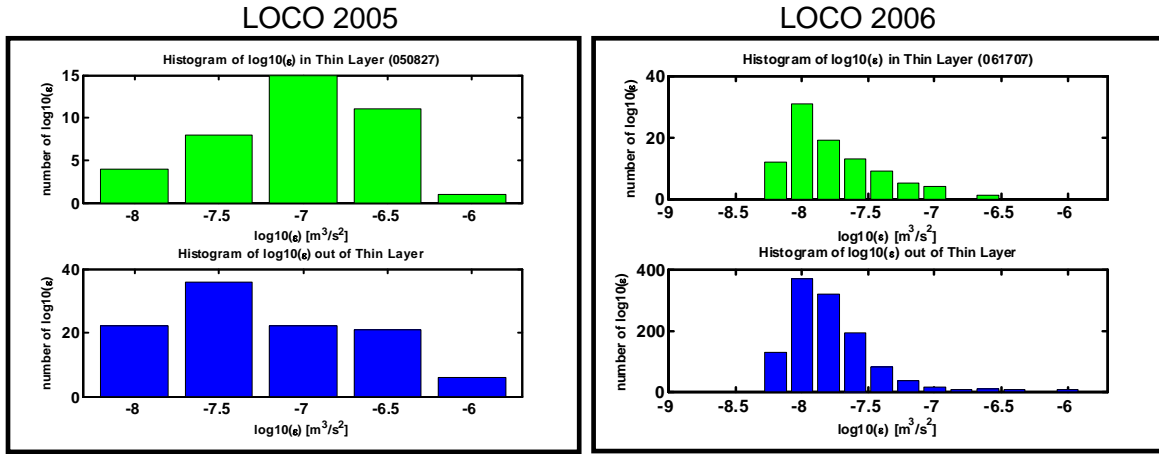
Figure 3. The histogram of TKE dissipation rate within and outside of the thin layers. (a) LOCO 2005 (b) LOCO 2006.

(2) The relationship of the thin layer thickness and turbulent diffusion.

From the preliminary statistics analysis of LOCO 2005 data, there appeared to be a significant correlation between phytoplankton layer thickness and the turbulent diffusive time scale (Fig 4). It should be noted that the dominant phytoplankton species in these thin layers was the dinoflagellate *Akashiwo Sanguinea*, which has considerable motility and can move with speeds up to (of order) several meters/hr. In general within the very thin layers (< 50 cm thickness) the turbulent rms velocity was observed to be of order or less than this speed. Thus Figure 4 suggests that for the thinness layers (< 50cm) to exist for more than an hour some type of quasi steady state condition must exist. This might be due to: (a) individual organisms using self propulsion to maintain their position along a density surface or (2) vertical settling onto a particular density surface at a sufficient rate to balance the turbulent dispersion. Fine scale shear also appears to play a very important role in developing very thin layers but further analysis needs to be made on this data set for quantification of this effect.

LOCO 2005 night cruises
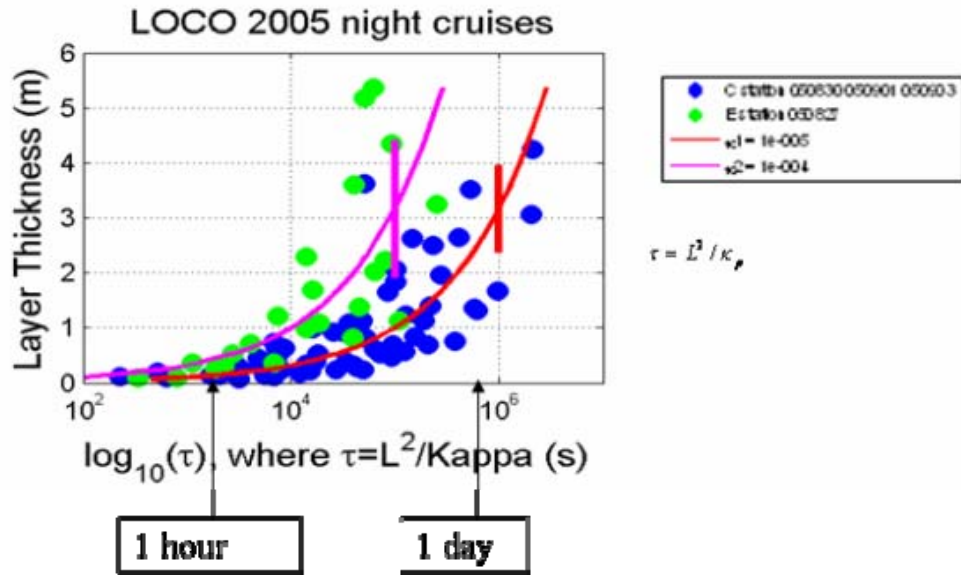
Figure 4. Turbulent diffusive time $\tau = L^2/\kappa$ versus the phytoplankton layer thickness L. κ is the eddy diffusivity, obtained directly within each thin layer. Green dots indicate data from the midnight Aug. 27th T-REMUS LOCO 2005 deployment. Blue dots indicate all other night runs during LOCO 2005. The magenta and red lines are the theoretical curves calculated by the turbulent diffusive time equation $\tau = L^2/\kappa$.

We will now very briefly present some results germane to the issue of the spatial structure of turbulence and its potential role in horizontal dispersion of phytoplankton. For this analysis we examine in detail one particular, data set obtained from 19:00 PDT, 17 July 2006 to 03:00 PDT, 18 July 2006.

Fig 2b shows as salmon color the 12 continuous T-REMUS track legs for this data set, all parallel to the fixed LOCO observatory stations, the "K" line. Note that these legs are approximately perpendicular to isobath contours. Each leg lasted about 40 minutes and alternated between an outbound one and an inbound one. The vehicle had a ground speed of 1.2 m/sec and performed 5° descent/ ascent yo-yos. It spanned depth ranges from 1.0 meters from the surface to 4m above the bottom. Each leg consisted of approximately 16 profiles with the horizontal distance between profiles being on average 150 meters. Eight hours of data were collected over the repeated cross isobath track of 2.7 kilometers. This sampling scenario not only allowed a detailed horizontal and vertical map of the turbulent field but also of the surrounding larger scale physical fields which drive the turbulence.

Figure 5 shows 12 contour plots of $\log_{10}(\varepsilon)$ as a function of across isobath range, r, and depth ,z. The origin of the abscissa, r = 0, is taken to be at the initial reference point at (36.942, -121.905). In addition to the dissipation rate shown in Figure 5 we also have detailed spatial data on temperature, salinity, density, vector current, chlorophyll-a, and optical scattering at 470 and 700 nm. Four specific regimes of turbulence are identified with strong turbulence ($\log_{10}(\varepsilon) \approx 10^{-7}$ W/kg and greater). These are: (1) surface "micro" frontal regions of warm water intrusion, seen in leg # 4 and Leg # 7 at the surface between ranges, r = -500 m and -1500m; (2) the edge of an internal solitary wave, seen in leg # 5 at r = -1000m, z =-8 m;; (3) the bottom mixed layer seen in legs 10, 11, and 12, between r = -1500 m

and r = -2500m; and (4) a broad region shown in legs 9 -12 centered between z = 5m and z = 10m meters extending across the entire section, with a large portion parallel to isopycnal surfaces.

The largest values of turbulence are observed in the "micro" frontal intrusion region which occurred near the surface (Leg #4 and Leg #7). We are now examining the source of this turbulence. Three possibilities are: i) geostrophic driven shear ; ii) plume sharpening from a solibore; (3) nighttime convection. We have also observed that observed regions of large solitary waves are not always coincident with strong turbulence but almost always are associated with a large density overturn, suggesting the possibility of capturing the beginning of a breaking Kelvin-Helmholtz like instability which has not yet evolved into active turbulence.
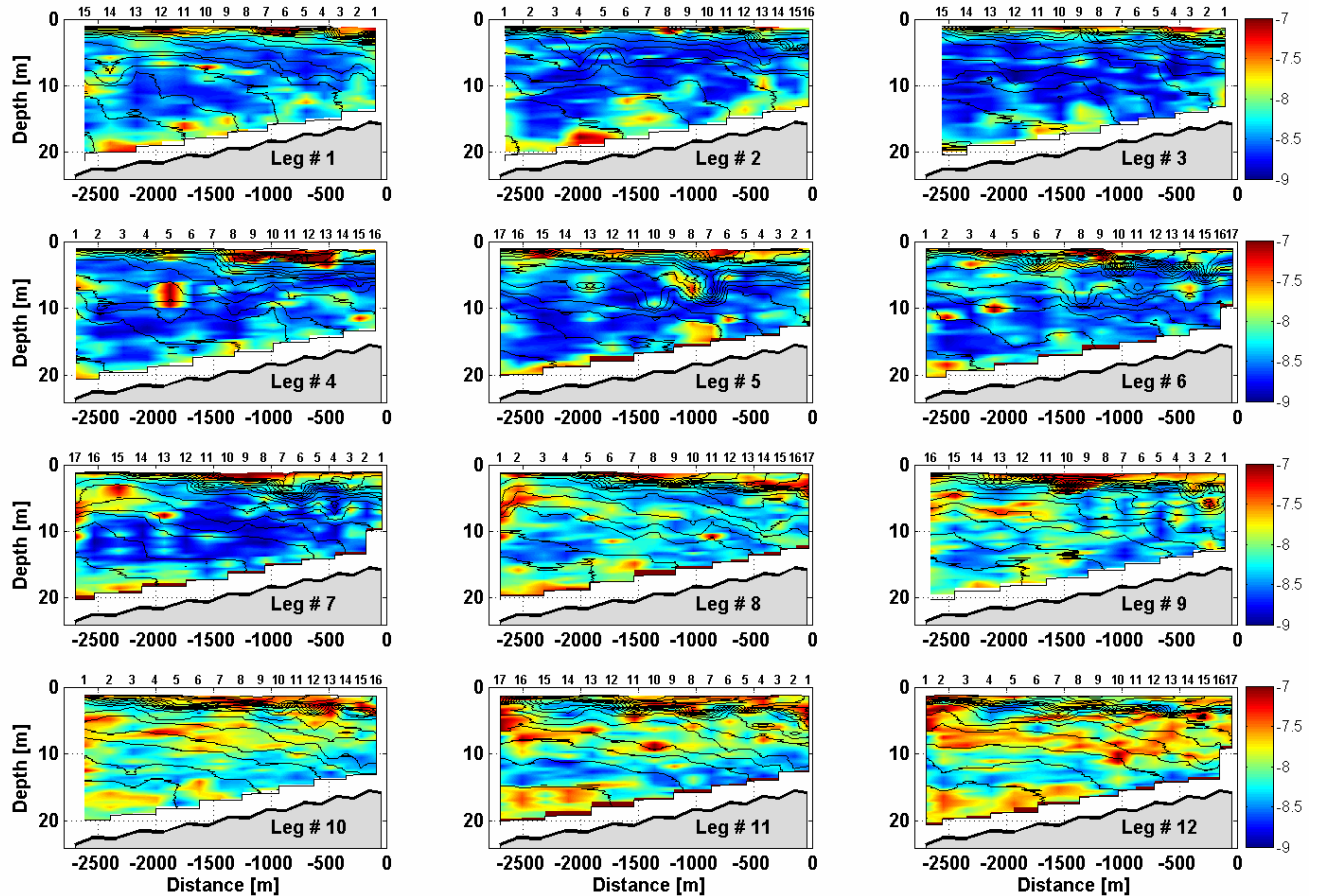
Figure 5. Contour of the $\log_{10}(\varepsilon)$ versus across isobath distance where ε is the dissipation rate in units of W/kg. Data were obtained from 07:00 PDT 17 July 2006 to 03:00 PDT 18 July 2006 along the track shown in Figure 2b. There were 12 legs, each of duration approximately 40 minutes. The vehicle preformed a 5 degree yo-yo. Individual profile locations are indicated by the number at the top of each individual contour. Dark lines indicate density contours.

The occurrence of turbulence in such specific regions clearly reveals that coastal turbulence can have a variety of sources of generation with each having their own unique horizontal structure. It has only been with the advent of sampling techniques such as those possible on the T-REMUS that we can

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reveal such structures. It is also important that we understand the relationship of fine scale parameters such as the Richardson number and the occurrence of turbulence. A critical Richardson number (below some value such as 0.25) only implies initial instability. It does not necessarily mean that this instability will result in fully developed, classical 3D turbulence. In other LOCO data sets (not shown) we are finding many instances of regions of large amplitude internal waves with low mean background Richardson numbers, having large overturns (of order meters) but low turbulence. Are these regions of turbulent events which are about to occur, have they already occurred, or are they regions which are not evolving into 3D turbulence? These are some of the fundamental questions which need to be addressed if we are to relate horizontal dispersion and mixing to turbulence and internal waves.

In Figure 6 we show a three dimensional map of chlorophyll-a and dissipation rate obtained from data taken by T_REMUS from 19:00 PST, 17 July 2006 to 03:00 PST, 18 July 2006. To obtain an along isobath, across track, horizontal scale we have used the mean water current advection velocity of 8 cm/sec, obtained from our ADCP measurements. As shown in the surface "quiver" plot of Figure 6, the mean current was on average perpendicular to the AUV track. Thus the across-track axis can also be considered as a time axis extending 8 hours. The green surface is chlorophyll-a, contoured using a surface value of 12 μg/L, a value typical of thin layers in LOCO 2006 (J. Sullivan, personal communication). Dissipation rate is contoured in blue with its surface value $\log_{10}(\varepsilon) \approx 10^{-7}$ W/kg. Note the along isobath structure for both chlorophyll-a as well as turbulence.

On 24 July, 2006 starting at 17:00 PST, ending 01:00 PST, 25 July, 2006 we performed an identical AUV experiment to that of 17 July, 2006. In Figure 7 for this experiment we show the same plot of data as in Figure 5. Clearly, in this case, the spatial structure of the turbulent and chlorophyll-a fields are much more strongly oriented across isobath rather than along isobath as in Figure 5.

On both days and throughout the experiment we estimate values of the local vertical diffusivity κ_v through the relationship

$$\kappa_v = \frac{\Gamma \varepsilon}{N^2} \qquad (1)$$

(Osborn, 1980), using the standard value of a mixing efficiency of Γ=0.2; N is the buoyancy frequency. Note that we obtain in the T-REMUS all of the terms in (1) at the same location and at the same time. Significant errors occur if this is not the case. For our data we find that overall κ_v, like ε, is approximately log normal in its statistics with an average value of κ_v of order 10^{-5} m^2/sNote that if we assume that features such as the chlorophyll-a shown in Figures 5 and 6 have evolved due to Fickian diffusion with initial length scales much less than the observed length scales, then we would expect that the horizontal diffusivity could be approximated by

$$\kappa_h = (\frac{l_h}{l_v})^2 \kappa_v$$

$$(2)$$

Examination of Figures 5 and 6 suggest that $\frac{l_h}{l_v} \approx \frac{1500}{3} = 500$ resulting in

$$\kappa_h \approx 2.5 \frac{m^2}{\text{sec}}$$

(3)

A number of points need to be raised about the assumptions inherent in this type of calculation. These are: (1) chlorophyll-a is not a perfect passive tracer; (2) the detailed (and possibly correlated) vertical and horizontal statistics of κ_v needs to be taken into account; (3) the simple length scale ratio of equation (2) needs to replaced by a more complete volumetric fitting of data taking into account both space and time dependence. None the less, it is interesting to note that the value in (3) is the same order of magnitude as predicted in Sundermeyer et al. (2005) but based on a simple Fickian diffusion argument. Data shown in Figure 5 suggests that large amplitude (internal solitary wave like) internal wave breaking in this particular region and during the time of this experiment was not the dominant driving mechanism of the turbulent field.
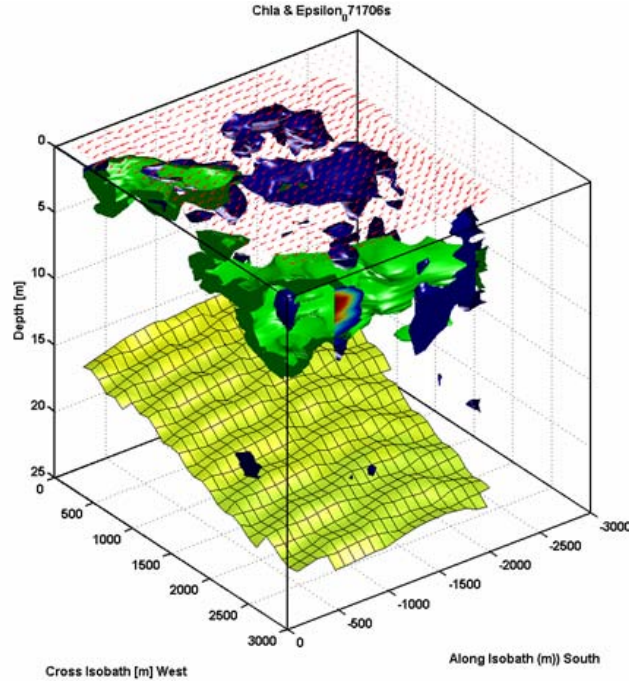
Figure 6. Three dimensional map of chlorophyll-a, green surface with a concentration of 12 μg/L, and turbulent dissipation rate, blue surface with $log_{10}(\varepsilon) \approx 10^{-7}$ W/kg. Data obtained from 17:00 PST, 17 July, 2006 to 01:00 PST, 18 July, 2006
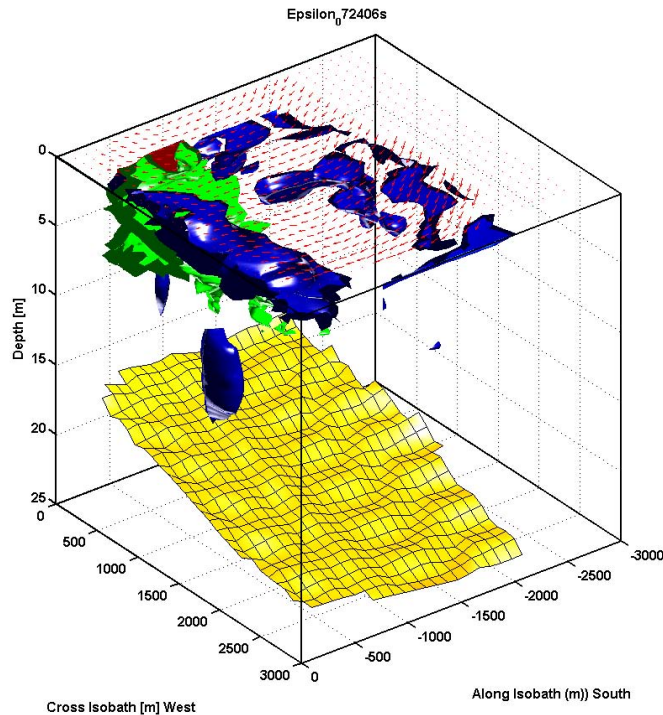
***Figure 7. Three dimensional map of chlorophyll-a, green surface with a concentration
of 12 μg/L, and turbulent dissipation rate blue surface with $\log_{10}(\varepsilon) \approx 10^{-7}$ W/kg.
Data obtained from 17:00 PST 24 July, 2006 to 01:00 PST 27 July, 2006.***

IMPACT/APPLICATIONS

To date, there is has been very few in situ studies on the direct effects of small-scale turbulence on thin layers. The platform T-REMUS provides a unique opportunity to quantify the spatial strcuture of the turbulence and fine scale fields and its relationship to thin layer formation evolutiona and breakdown.

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